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Preliminary Study of *Melastoma Malabathricum L.* Leaf Extract as a Green Corrosion Inhibitor for Car Radiator

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ABSTRACT

Corrosion in automotive cooling systems is a persistent issue that compromises efficiency and component lifespan. Synthetic corrosion inhibitors commonly used in radiator coolants help mitigate corrosion but have raised environmental concerns due to their toxic byproducts. This study evaluates tannin extracted from *Melastoma Malabathricum L.* leaves as a natural, eco-friendly corrosion inhibitor. Tannin was extracted using the solvent extraction method and characterised by XRD and FTIR. The corrosion resistance of aluminium substrates in car radiators was tested in various mediums (HCl, NaOH, deionised water, and radiator coolant) over 24, 48, and 72 hours using the weight loss measurement (WLM) method. Results revealed significant corrosion rate and inhibition efficiency, particularly in NaOH, supported by reduced weight loss and improved microstructural stability. These findings highlight tannin's potential as a sustainable alternative to synthetic corrosion inhibitors.

Keywords: Corrosion inhibitor, Melastoma Malabathricum L. leaf, tannin, weight loss measurement, automotive cooling systems

1. Introduction

Corrosion is a critical problem in the automotive industry, particularly impacting cooling systems and related components. Aluminium, commonly used in car radiators due to its high thermal conductivity and lightweight nature, is particularly vulnerable to corrosion when exposed to aggressive environments, such as those involving acidic or basic solutions [1]. The corrosion process can compromise the structural integrity and efficiency of cooling systems, leading to increased maintenance costs and reduced vehicle longevity [2-3].

The use of synthetic corrosion inhibitors has been a widespread practice in addressing these challenges. Such inhibitors, including silicates and phosphates, are effective in protecting metal surfaces but come with significant drawbacks. These chemical compounds can release toxic byproducts into the environment, contributing to pollution and posing health risks [4]. The shift towards environmentally sustainable practices has motivated researchers to explore natural corrosion inhibitors, which are derived from plant sources and offer a greener alternative with minimal ecological impact [2-5].

Tannin, a naturally occurring polyphenolic compound, has garnered attention as a potential green corrosion inhibitor. It is found abundantly in plant tissues, including the bark, leaves, and fruit of various species. Tannins possess a unique combination of high thermal stability and strong adsorption capabilities due to their multiple hydroxyl groups, which facilitate the formation of protective layers on metal surfaces [6]. These properties make tannins suitable for high-temperature applications, such as those encountered in automotive radiators.

Melastoma Malabathricum L., a plant native to tropical regions such as Malaysia, is known for its rich tannin content and has been traditionally used for medicinal purposes [7]. However, its potential as a corrosion inhibitor has not been extensively explored. The adsorption of tannin molecules on metal surfaces occurs through chelation or hydrogen bonding, forming a stable passivation layer that can impede the interaction between the metal and corrosive agents [8]. This study focuses on evaluating the effectiveness of tannin extracted from *Melastoma Malabathricum* L. leaves as a corrosion inhibitor for aluminium substrates.

Previous studies have demonstrated the efficacy of natural extracts, such as those derived from plants like *Azadirachta indica* and *Camellia sinensis*, in reducing the corrosion rates of metals [9]. These studies highlighted the role of phenolic compounds, particularly tannins, immersion time (24hours, 48hours and 72hours), in the adsorption and formation of protective layers on metal surfaces. However, there is limited research specifically addressing the use of tannin from *Melastoma Malabathricum* L., which this study aims to explore in depth.

2. Materials and Methods

2.1 Preparation and Characterisation of Aluminium Substrate

The aluminium substrates used in this study were obtained from car radiator components and selected for their representative composition as part of the 2xxx aluminium series. The preparation involved cutting the aluminium sheets into uniform 1 cm^2 samples. These samples were polished using a sequence of sandpapers (400, 800, and 1000 grit) to remove surface impurities and achieve a smooth, uniform surface. Each polished sample was cleaned with deionised water and acetone to ensure the removal of any residual debris or oils. The chemical composition of the aluminium was verified using X-ray fluorescence (XRF) analysis to confirm its suitability for corrosion testing.

2.2 Extraction and Characterisation of Tannin from *Malestoma Malabathricum L.* leaf

2.2.1 Tannin Extraction Process

The tannin extraction was performed using *Melastoma Malabathricum* L. leaves, which were collected at Agro Techno Park, UMK Jeli Campus, Kelantan, and thoroughly washed to remove impurities. The leaves were dried in a shaded area for 72 hours to prevent photodegradation and then sieved 100 µm into a fine powder using a mechanical grinder. A solvent extraction method was chosen for its efficiency in isolating tannin compounds. Specifically, 5 grams of leaf powder were added to 200 mL of absolute ethanol and heated at 50-60°C for 100 minutes using a reflux setup. This process allowed for optimal extraction of tannin without significant degradation of bioactive compounds. After cooling, the mixture was centrifuged at 4000 rpm for 15 minutes to separate the supernatant, which contained the tannin extract, from the plant residue. The supernatant was then filtered using Whatman No. 1 filter paper and concentrated using a rotary evaporator at 45°C to remove the solvent, resulting in a viscous tannin extract.

2.2.2 Characterisation of Tannin

Qualitative and quantitative analyses were conducted to determine whether the tannin was present in the extract. X-ray diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) were used to characterise the powder leaf sample before *Melastoma Malabathricum L.* tannin extraction. The percentage of crystallinity and composition were determined using XRD, and the chemical bonds and functional groups present in the sample were identified using FTIR.

2.2.3 Qualitative

The qualitative analysis of the extract was tested using the ferric chloride method. An amount of 0.811g of iron (III) chloride powder will be diluted with 20 ml of distilled water in a volumetric flask. It was stirred until it was fully

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incorporated and was stored in a test tube with a cap. Using a micropipette, 200µL of sample and 2 drops of diluted iron (III) chloride were added into a test tube. Indication of dark blue colour indicates the presence of tannin.

2.2.4 Quantitative

The quantitative analysis of the extract was tested using a UV-Vis Spectrophotometer. Two samples were tested during the quantitative analysis, which were the samples before and after undergoing the rotary process. Both samples were diluted using 0.1M of HCl. The dilution process was doubled with a ratio of (1:100 / sample: solvent) for the first dilution and a ratio of (1:50) for the second dilution. The diluted sample was added into a glass cuvette and inserted into the chamber of the UV-Vis Spectrophotometer. Each sample was tested 3 times, and results were tabulated.

2.3 Corrosion Inhibition Study

During this corrosion inhibition study, aluminium substrates were immersed into 4 mediums which are hydrochloric acid (HCl), sodium hydroxide (NaOH), deionised water (DW) and car radiator coolant. The parameters were duration of immersion. The results obtained were used to calculate the weight loss measurement (WLM) method.

2.3.1 Preparation of Corrosion Medium

Before the set-up of corrosion inhibitor testing, the pH of corrosion mediums was tested. The pH meter was dipped into beakers with different mediums (HCl, NaOH, deionised water and car radiator coolant). HCl solution (0.1M) simulates an acidic environment, NaOH solution (0.1M) represents an alkaline condition, and Deionized water serves as a neutral test medium and commercial radiator coolant Used to assess the tannin's performance in a real-world scenario.

2.3.2 Weight Loss Measurement (WLM) Method

The corrosion rate and inhibition efficiency were assessed using the WLM method. Each aluminium sample was accurately weighed before immersion using an analytical balance with a precision of 0.001 g. The samples were then fully immersed in 200 mL of each test medium, with and without the addition of 1% (v/v) tannin extract. The immersion times were set at 24, 48, and 72 hours at room temperature.

After the designated exposure periods, the samples were removed, rinsed with deionised water, dried in a desiccator, and reweighed. The weight loss was used to calculate the corrosion rate (CR) using the following formula:

$$Corrosion\ Rate = \frac{W1-W2}{At} \qquad (1)$$

$W1$= weight value of substrate before immersion
$W2$= weight value of substrate after immersion
A= area of substrate
t= time of immersion

Inhibition Efficiency (IE) was calculated using the corrosion rate in the presence of an inhibitor and the corrosion rate in the absence of an inhibitor. The equation will be shown below:

$$Inhibition\ Efficiency\ (IE\ \%) = \frac{CRa-CRp}{CRa} \times 100 \qquad (2)$$

CRp= Corrosion rate with presence of inhibitor
CRa= Corrosion rate with absence of inhibitor

3. Results and Discussion

3.1 Characterisation of Aluminium Substrate

The aluminium substrate used in this study was characterised using X-ray fluorescence (XRF) to determine its elemental composition. The results are shown in Table 1.

Table 1: Chemical composition of Aluminium substrate

Elements	Weight percentage (wt.%)
Mg	3.97
Al	93.38
Si	1.49
Ti	0.07
Mn	0.54
Fe	0.14
Cu	0.02
Zn	0.24
Zr	0.02
Sc	0.01
Sn	0.01
Total	**99.89**

The chemical composition confirms that the aluminium substrate belongs to the 2xxx series alloys, known for their high strength and application in structural and heat-conductive environments. The relatively high content of magnesium enhances mechanical properties but also requires careful consideration for corrosion resistance, especially in acidic and alkaline environments. The presence of silicon and manganese contributes to enhanced wear resistance and overall mechanical stability, which is beneficial for automotive components exposed to high thermal and mechanical stress. This elemental composition has a direct impact on how the aluminium reacts under different corrosive conditions, influencing the effectiveness of corrosion inhibitors such as tannin in providing adequate protection.

3.2 Extraction and Characterisation of Tannin from *Malestoma Malabathricum L.* leaf

3.2.1 Characterisation of Melastoma Malabathricum L. Prior to Extraction

Prior to the tannin extraction of *Melastoma Malabathricum L*, characterisation of the powder leaf sample was conducted using X-ray diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR). XRD was used to detect the percentage of crystallinity and composition, while FTIR was used to detect the chemical bonds and functional groups that exist in the sample. Fig. 1 shows the XRD Peak of powder *Melastoma Malabathricum* L. leaf while Fig. 2 shows the FTIR Peak of powder *Melastoma Malabathricum L*. leaf.

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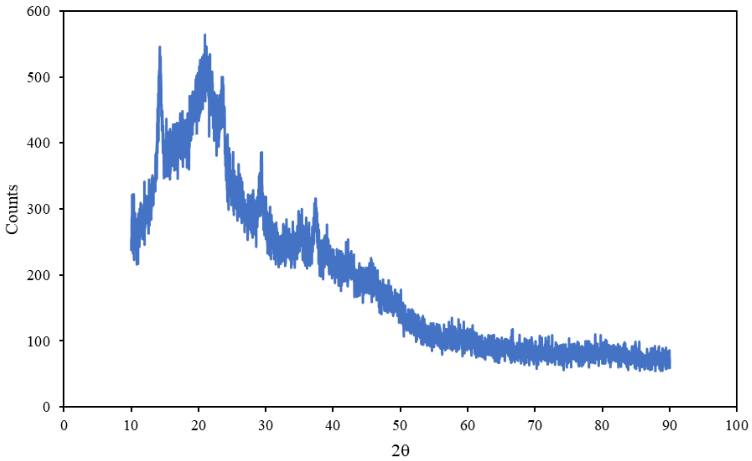

Fig. 1: XRD Peak of Powder *melastoma malabathricum L*. leaf.

According to Fig.1, the XRD pattern shows an amorphous feature with a broad peak. The phrase amorphous is commonly applied to the texture that lacks any correspondence with the “crystalline” phase [10]. The XRD result measured the crystallinity % of the *Melastoma Malabathricum* L. leaf sample at 21.7% and amorphous at 78.3%, which indicates that it is majorly amorphous content. The XRD result of Aloe Vera plant powder showed a similar XRD pattern that indicates an amorphous feature [11]. Therefore, we can conclude that the powder *Melastoma Malabathricum* L. leaf is an amorphous sample.

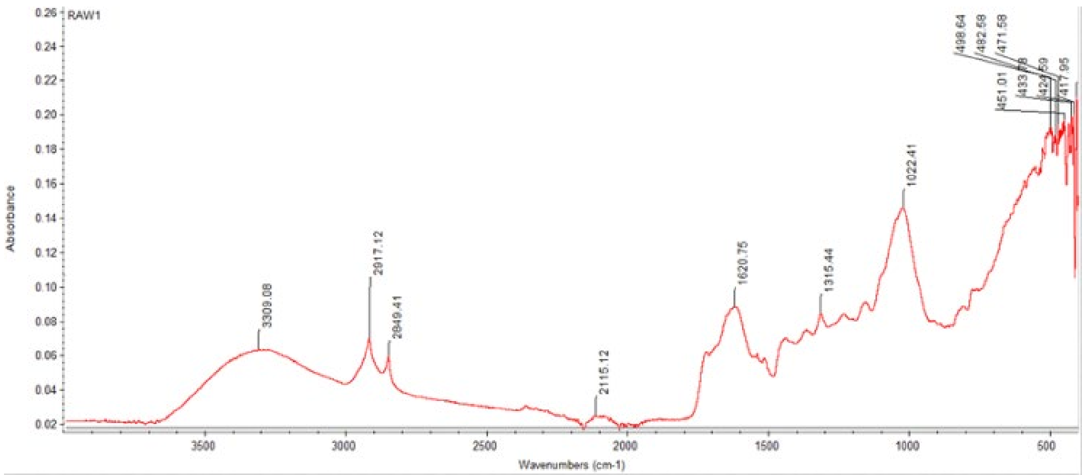

Fig. 2: FTIR Peak of Powder *Melastoma Malabathricum L*. leaf

The results in Fig.2 show the spectrum of plant extract. The peak at 3309.08 indicates the weak stretch presence of the O-H (alcohol) bond. Both the 2917.12 and 2849.41 peaks showed a medium stretch presence of a C-H (hydroxyl) bond. After that, at peak 2115.12, it showed a weak stretching presence of C≡C (alkyne). Next, stretch at 1620.75 indicates the presence of a strong C=C (alkene) bond. The stretch peak at 1315.44 showed a strong C-F (methyl) bond. Lastly, the peak at 1022.41 showed a C-O (oxygen ether) bond. Based on the FTIR peak, it indicated that the powder *Melastoma Malabathricum L*. leaf had functional groups of alcohols, alkene, alkyne, hydroxyl, methyl, and oxygen ether, similar to the previous findings [12].

3.2.2 Qualitative Analysis of Extracted Tannin

Qualitative analysis was conducted to detect the presence of tannin in the extract. The qualitative analysis followed the phytochemical screening, which uses the ferric chloride method. Fig.3 (a) shows the tannin extract before adding iron (III) chloride, and Fig.3 (b) shows the tannin extract after adding iron (III) chloride.

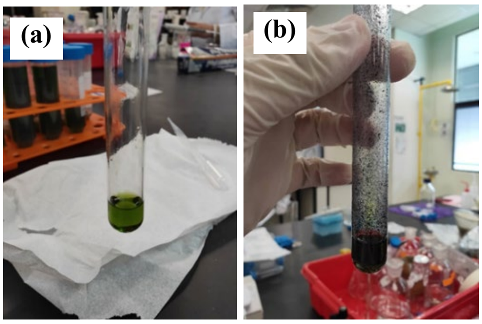

Fig.3 Tannin extract (a) before and (b) after adding iron (III) chloride

The qualitative analysis of the extract was performed using the ferric chloride method. From Fig.3 (a) the tannin extract was greenish colour before adding iron (III) chloride. As for Fig.3 (b), after adding in the iron (III) chloride, the formation of a dark blue precipitate was observed. This indicated the presence of tannin in the extract. In a similar study, Kamal et al. [13] have also utilised the same method to detect the presence of tannin from *Chromolaena Odorota sp*. Once the presence of tannin is detected, quantitative analysis needs to be conducted to identify the concentration of tannin.

3.2.3 Quantitative Analysis of Extracted Tannin

For the quantitative analysis of extracted tannin, UV-Vis Spectroscopy was used to detect the concentration of tannin. There were 2 samples tested, which are tannin extract before and after rotary evaporation. Table 2 shows the quantitative analysis of extracted tannin from *Melastoma Malabathricum* L. leaf.

According to Table 2, the UV spectroscopy method was conducted for both tannin extract before rotary evaporation and tannin extract after rotary evaporation to identify which of these extracts has a greater content. The wavelength concentration range was set at 276 nm as followed by Beer Lambert's law [14]. The correlation coefficient (r^2) was calculated where it is valued at 0.9909, indicating that the absorbance and concentration have a good linearity. To obtain accuracy and precision, tannin extract before rotary evaporation and tannin after rotary evaporation samples were tested 3 times to obtain the mean value of 0.035 and 0.335, respectively. The relative standard deviation (RSD%) value of tannin extract before rotary evaporation and tannin after rotary evaporation samples were found to be 0% and 69%, respectively. The actual concentration of tannin extract before rotary evaporation and tannin after rotary evaporation was calculated using the linear equation, and the values were 0.607 and 7.296, respectively, showing an obvious difference between both samples. Therefore, tannin extract after rotary evaporation was selected for the corrosion inhibitor study.

Table 2: Quantitative Analysis of Extracted Tannin

Samples	Reading 1	Reading 2	Reading 3	Mean	Standard Deviation	RSD %	Actual Concentration
Before R/E	0.035	0.035	0.035	0.035	0	0%	0.607
After R/E	0.332	0.336	0.336	0.335	0.002	69%	7.296

R/E represent Rotary Evaporation

RSD represent Relative Standard Deviation
Linear equation = $y= 0.0448x + 0.0078$
$R^2= 0.9909$

3.3 Corrosion Inhibitor Study using Weight Loss Measurement (WLM) method

In this experimental work, four mediums were used: hydrochloric acid (HCl), sodium hydroxide (NaOH), deionised water, and car radiator coolant. Hydrochloric acid was prepared at a concentration of 0.1M, and it acts as the acidic medium among the other mediums. Sodium hydroxide was also prepared at the same concentration at 0.1M and it represents the alkaline medium. Deionised water represents the neutral medium, and the car radiator coolant is the conventional medium that contains synthetic corrosion inhibitors. Each of these mediums was tested with and without the addition of tannin, which acts as the natural corrosion inhibitor, except for car radiator coolant, as it already has synthetic corrosion inhibitor contents. To examine the corrosion testing, aluminium substrates are cut out from a car radiator to represent the actual scenario for the application purpose.

3.3.1 pH of Corrosion Mediums

During the set-up for the corrosion inhibitor study, the mediums (HCl, NaOH, deionised water and car radiator coolant) were tested. HCl (pH2.8), NaOH (pH13.8), deionised water (pH6.3), and car radiator coolant (pH9.2).

3.3.2 Percentage of Weight loss

Table 3 and Fig. 4 show the weight loss of aluminium substrate in HCl, NaOH, deionised water and car radiator coolant (with and without tannin), with immersion time of 24 hours, 48 hours, and 72 hours.

Table 3: Weight loss of aluminium substrate in all medium

Medium	24h With Tannin (%)	24h Without Tannin (%)	48h With Tannin (%)	48h Without Tannin (%)	72h With Tannin (%)	72h Without Tannin (%)
HCl	-2.86	2.77	0	2.4	2.86	7.59
NaOH	32.38	39.45	28.09	28.21	29.84	4.29
Deionized Water	-18.45	-14.05	0.76	-2.8	-2.72	-1.85
Car Radiator Coolant	0	0	0	-5.13	0	-2.52

According to Table 3 and Fig. 4, the weight loss data from the corrosion tests on aluminium substrates immersed in different mediums over varying periods (24, 48, and 72 hours) reveal distinct trends that reflect the effectiveness of tannin as a corrosion inhibitor. In an acidic medium (HCl), a consistent trend of reduced weight loss was observed for samples treated with tannin compared to those without. This indicates that tannin forms a protective film on the aluminium surface that effectively minimises metal dissolution. Over 72 hours, the sample with tannin exhibited significantly less corrosion than the untreated sample, underscoring its potential as an inhibitor in acidic environments. This trend suggests that tannin's protective capability strengthens over time as it adheres and stabilises on the metal surface.

In contrast, in an alkaline medium (NaOH), the data showed more variability. Initially, at the 24-hour mark, both treated and untreated samples demonstrated significant weight loss, but the presence of tannin resulted in a relatively lower rate. Over 48 and 72 hours, the tannin-treated samples showed a reduction in weight loss, though with some fluctuations. This may be attributed to the interaction between tannin and the alkaline solution, where the protective layer may partially degrade or require more time to reform. Despite these variations, tannin still exhibited overall effectiveness by consistently reducing the weight loss compared to samples without it, indicating that its protective properties remain beneficial, albeit with limitations in high pH environments.

In neutral conditions (deionised water), a unique trend was observed where both treated and untreated samples gained weight initially, particularly within the first 24 hours. This increase in weight suggests the formation of a passive oxide film, which is typical for aluminium in neutral or slightly corrosive conditions. The tannin-treated samples displayed a greater initial weight increase, implying that tannin enhances the formation of this passive film, thereby

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providing additional protection against further corrosion. Over 48 and 72 hours, slight variations in weight were noted, but the presence of tannin continued to support a stable protective barrier on the metal surface.

For car radiator coolant, which contains pre-existing synthetic corrosion inhibitors, the trends showed minimal weight changes. The slight negative weight loss percentages, particularly at the 48- and 72-hour marks, indicate an increase in weight, likely due to the stabilisation and potential thickening of the protective layer formed by the synthetic inhibitors. The addition of tannin did not significantly alter the corrosion protection, suggesting that when strong synthetic inhibitors are already present, tannin's impact is limited. This highlights that tannin may be more beneficial in mediums lacking strong existing corrosion prevention measures.

Overall, the trends in the weight loss data emphasise that tannin extracted from *Melastoma Malabathricum* L. is most effective in acidic and neutral conditions, where it actively contributes to forming a robust protective layer. In alkaline environments, while tannin demonstrates clear inhibition properties, its effectiveness may vary due to interactions with the medium. In pre-treated environments like car radiator coolant, tannin's influence is minimal as the medium already possesses substantial protective mechanisms. These observations collectively underscore tannin's potential as an environmentally friendly corrosion inhibitor with significant efficacy under certain conditions.

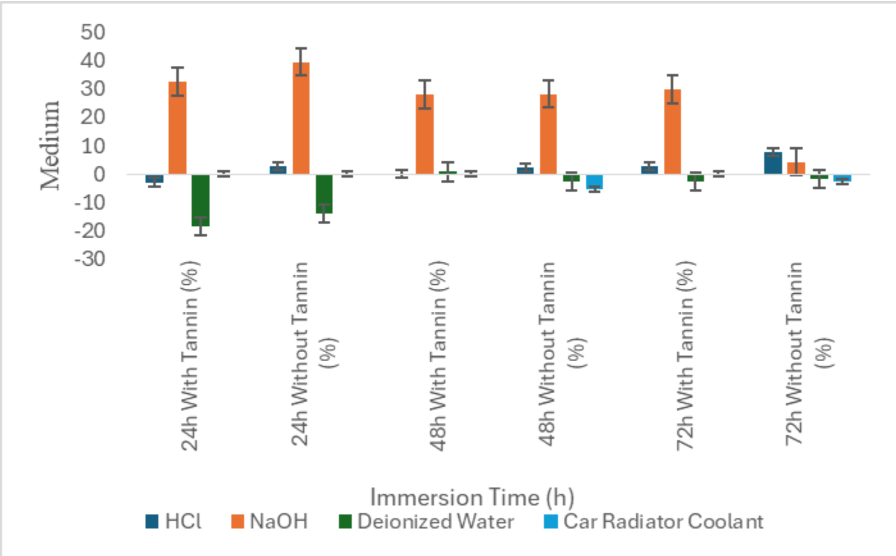

Fig.3: Weight loss percentage of tannin in all medium

3.3.3 Corrosion Rate

Table 5 and Fig. 5 show the corrosion rate of aluminium substrate immersed in HCl, NaOH, deionised water and car radiator coolant (with and without tannin) for 24 hours, 48 hours and 72 hours respectively.

Table 5: Corrosion rate of aluminium substrate immersed in all medium

Medium	24h With Tannin ($g/m^2/h$)	24h Without Tannin ($g/m^2/h$)	48h With Tannin ($g/m^2/h$)	48h Without Tannin ($g/m^2/h$)	72h With Tannin ($g/m^2/h$)	72h Without Tannin ($g/m^2/h$)
HCl	-0.072	0.072	0	0.072	0.096	0.264
NaOH	0.816	1.032	1.632	1.584	2.664	0.504
Deionized Water	-0.456	0.408	-0.144	-0.048	-0.36	-0.216
Car Radiator Coolant	0	0	0	-0.288	0	-0.216

Based on Table 5 and Fig. 5, the trends in the corrosion rate data provide a comprehensive view of how tannin affects the corrosion of aluminium in various environments over time. In the acidic medium (HCl), the presence of tannin consistently reduced the corrosion rate compared to the untreated samples, particularly noticeable at 72 hours. For instance, the 72 hour corrosion rate with tannin was 0.096 $g/m^2/h$, while without tannin, it was 0.264 $g/m^2/h$. This trend confirms tannin's ability to form a protective film that limits the reaction between the aluminium and the acidic solution, effectively reducing corrosion over time.

In the alkaline medium (NaOH), tannin showed a variable impact. At 24 hours, the corrosion rate with tannin (0.816 $g/m^2/h$) was lower than without it (1.032 $g/m^2/h$), indicating initial inhibition. However, by 72 hours, the corrosion rate for the tannin-treated sample increased to 2.664 $g/m^2/h$, which was higher than the untreated sample (0.504 $g/m^2/h$). This suggests that while tannin can provide initial protection in an alkaline environment, the stability of the protective film may degrade over extended periods, allowing corrosion to progress more rapidly.

In neutral conditions (deionized water), both treated and untreated samples displayed negative corrosion rates at certain points, indicating an increase in weight due to the formation of a passive oxide film. For instance, the 24-hour rate with tannin was -0.456 $g/m^2/h$, suggesting that tannin aids in enhancing this film. However, over 72 hours, the corrosion rates indicated slight weight decreases, showing that while the protective layer remains, it may be thinner or less robust over time.

For car radiator coolant, the corrosion rates were minimal and relatively stable, reflecting the effectiveness of pre-existing synthetic inhibitors in the coolant. The addition of tannin did not significantly affect the corrosion rate, with rates close to zero or slightly negative at various intervals. This indicates that tannin does not add substantial inhibition where effective synthetic inhibitors are already present.

Overall, the data demonstrate that tannin is particularly effective in reducing corrosion in acidic environments, showing strong initial and sustained protection. In alkaline conditions, while tannin provides some protection, its effectiveness varies over longer durations, potentially due to the breakdown of the protective layer. In neutral and synthetic inhibitor environments, tannin's contribution is either beneficial for enhancing passive film formation or negligible due to existing inhibitors.

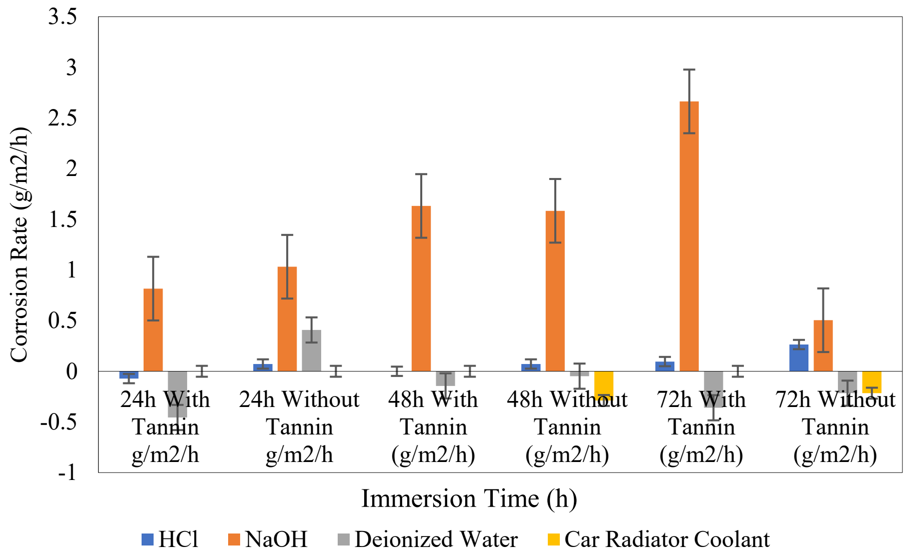

Fig. 4: Corrosion rate of aluminium substrate

3.3.4 Inhibition Efficiency

The inhibition efficiency was used to calculate the efficiency of tannin as an inhibitor in different mediums (HCl, NaOH, deionised water and car radiator coolant). The inhibition efficiency of the tannin in different mediums and different immersion times was calculated and discussed in this section. Table 6 and Fig. 6 show the inhibition efficiency of HCl, NaOH, and deionised water at 24 hours, 48 hours, and 72 hours.

Table 6: Inhibition Efficiency of HCl, NaOH and Deionised Water

Immersion Time	Inhibition Efficiency (%)		
	HCl	NaOH	Deionised water
24 hours	200	96.71	211.76
48 hours	100	97.85	-200
72 hours	63.64	92.66	-66.67

Table 6 shows the inhibition efficiency of tannin extract in HCl as an acid medium, NaOH alkaline medium and deionised water as the neutral medium. In the first 24 hours, the inhibition efficiency of tannin in HCl is up to 200%, which is slightly lower compared to deionised water at 211.79%. As for NaOH, it had an efficiency of 96.71%. Hence, with an immersion time of 24 hours, all three mediums have high inhibition efficiency rates. At 48 hours, the inhibition efficiency for aluminium substrate in deionised water seems to be lower from 200% to -200%. This might indicate at 48 hours; the rate of corrosion seems to have accelerated much faster compared to the passivation of thin protective film. As for inhibition efficiency in HCl, it is much lower compared to 24 hours at 100%, and for NaOH, it is slightly higher at 97.85%. At 72 hours, the inhibition efficiency in HCl is at 63.64%, NaOH at 92.66% and deionised water at -66.67%. According to the results, NaOH seems to have the most consistent inhibition efficiency at 96.71% for 24 hours, 97.85% for 48 hours and 92.66% for 72 hours. As discussed in section 4.3.1, car radiator coolant is an alkaline medium similar to NaOH. In this study, we found that tannin from *Melastoma Malabathricum* L. works well in NaOH despite the corrosion rate. This is because the adsorbed inhibitor molecules on the metal surface result in a higher surface coverage. The adsorbed molecules form a film over the corroding metal [8]. In conclusion, it seems like an alkaline medium can be a suitable medium and have a better inhibition efficiency compared to the other mediums.

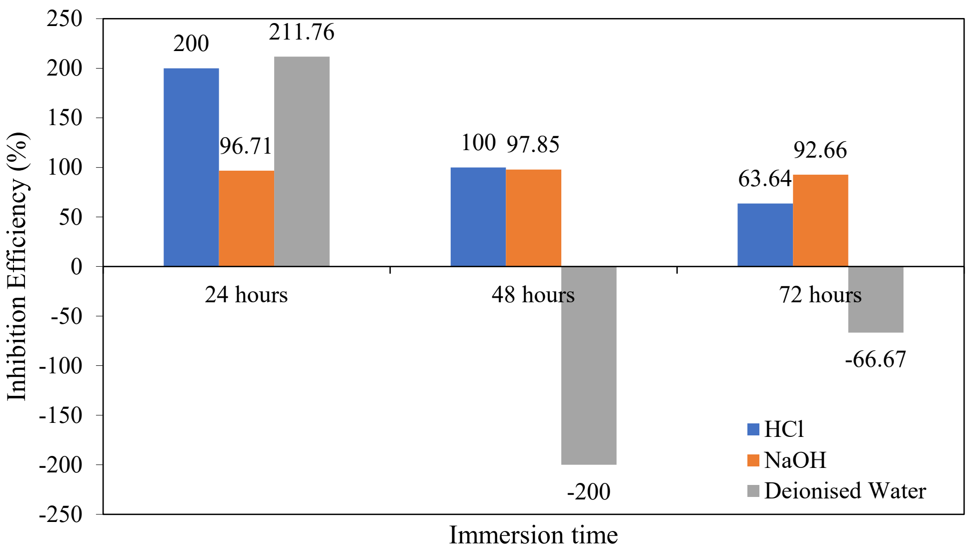

Fig. 5: Inhibition efficiency of different mediums and different immersion time

4. Conclusion

In conclusion, tannin extracted from *Melastoma Malabathricum L.* has proven to be an effective, eco-friendly corrosion inhibitor, particularly in acidic and neutral environments. The data demonstrate that tannin significantly reduces weight loss and corrosion rates, showcasing high inhibition efficiency by forming a stable protective film on the aluminium surface. While the effectiveness is clear in acidic mediums, its performance in alkaline environments is more variable, suggesting potential limitations in the long-term stability of the protective layer. In mediums already containing synthetic inhibitors, such as car radiator coolant, tannin's impact is minimal, indicating its most effective use is in untreated or less-protected systems. These findings highlight tannin's potential as a sustainable alternative to synthetic inhibitors, especially where environmental considerations are prioritised, though further research could improve its stability and performance in diverse conditions.

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